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Key Technologies of EV Motor Drive System Design

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Abstract

For pure Electric Vehicle (EV), motor is the one and only power source. Comparing with industry motor, the motor drive system in EV has several challenges, such as dynamic running with unpredicted drive cycle, high torque/power density to reduce the vehicle curb weight, robust limp-home functionality to ensure vehicle can run even when some key components failed, life-time guarantee, wide speed control range, etc. This paper gives detail description about these key technologies in EV motor drive system design, such as weakening control, torque accuracy, and limp-home strategies, etc. It can be provided as a good reference for EV motor drive system design.

Keywords: Electric vehicle (EV); motor drive system; weakening control; torque accuracy

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1. Introduction

With the deterioration of energy shortage and environmental pollution, the research of new energy vehicles gets more and more attention from Governments and manufactures. In China, the Government already released the policy of providing subsidies to EV and plug-in hybrid vehicle to strongly encourage the volume production of new energy vehicles. Meanwhile, there are some technical bottle-necks in EV design. Motor drive system design is one of the core technologies [1-3]. In this paper, five key technologies in EV motor drive system design are introduced, which includes weakening control, limp-home strategies, torque accuracy, efficiency of motor drive system, and max motor speed limitation.

2. Motor type selection

For EV, there are many types of motor can be used to drive the vehicle, such as DC motor, induction motor, and permanent magnet synchronous motor (PMSM), etc. The selection of motor type must balance between motor drive system performance and system cost. Meanwhile, motor drive system also includes

motor drive device (e.g. inverter) and motor itself. Currently, these three types of motor are both used in different EV projects. To design a motor drive system, the first job is selecting the motor type based on vehicle level requirements and some other boundary conditions. There is no single optimized solution, but need to select the motor drive system case by case. In this paper, the characteristics of these motors will be compared and then choose one motor as the design focus.

DC motor is the simplest motor, which uses mechanical brush commutation, prone to wear and tear, the failure rate is high and difficult to maintain. At the same time, DC motor has larger drive system, narrow speed control range, low energy density, which limit the usage of DC motor in EV applications, only some electric bicycle use the DC motor. Induction motors and PMSM have electronically commutation, which overcome the shortcomings of mechanical brush commutation, and use sine wave control mode to implement high precision torque control. Table 1 is the characteristics comparing of these two motors.

Table 1. Comparison of motor performance

	PMSM	Induction motor		PMSM	Induction motor		PMSM	Induction motor
Space	+	o	Air gap	+	o	Noise	+	+
Winding	+	o	Sensors	o	+	Inverter cost	+	-

As shown in table 1, PMSM has good overall performance, such as high control accuracy, high power density and low noise, etc. So PMSM is widely used in the EV motor drive system. The design of this paper also selects PMSM drive system as the study focus. PMSM is controlled by a three-phase inverter circuit, includes six semiconductor switching devices controlled by the PWM signals that generated by the motor controller. Then three-phase sinusoidal voltage signal are produced, as shown in Fig. 1.

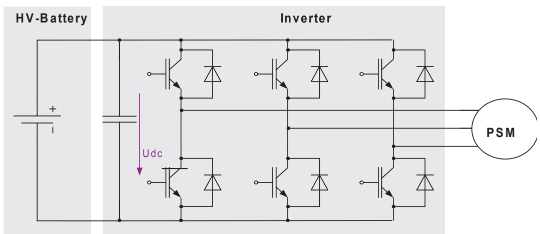


Fig. 1. Three-phase PMSM inverter circuit

3. Key technologies of motor drive system

Motor drive system is one of the core components of EV, which requires high torque at low speed, high-power at high speed, wide speed control range to meet the EV performance requirements. This section will presented five key technologies in EV motor drive system design.

3.1. Weakening control

For PMSM control, since the super scale of inverter DC bus voltage can lead to the saturation of current regulator, so as to limit the motor maximum speed. In order to obtain wider speed control range, motor field weakening control is necessary. The basic idea of PMSM weakening control comes from the tone of excited magnetic DC motor control, when the motor voltage reaches the maximum voltage, by reducing the exciting current of the motor to change the excitation flux, to ensure the voltage balance under the conditions of the motor to be constant power operation at higher speed. For the PMSM motor, permanent magnet inside the rotor can not be adjusted, it can only by adjusting the stator current, by increase of the magnetic circuit of stator direct axis component to reduce the excitation current to achieve and maintain the balance of high-speed operation voltage to achieve flux weakening.

PMSM motor torque can be calculated with following formula:

$$T_{em} = \frac{3}{2} p[\psi_f I_q + (L_d - L_q) I_d I_q] \tag{1}$$

MPTA (Maximum Torque per Ampere) curve is the shortest distance from the torque operating point to the origin.

$$\begin{cases} \dfrac{\partial T_{em} / I_s}{\partial I_d} = 0 \\ \dfrac{\partial T_{em} / I_s}{\partial I_q} = 0 \end{cases} \tag{2}$$

The equation is solved as follows:

$$I_d = \frac{\psi_f}{2(L_d - L_q)} - \sqrt{\frac{\psi_f^2}{4(L_q - L_d)^2} + I_q^2} \tag{3}$$

$$T_e = \frac{3}{2} p[\psi_f + (L_d - L_q) I_d] \sqrt{\frac{\psi_f I_d + (L_d - L_q) I_d}{L_q - L_d}} \tag{4}$$

$$T_e = \frac{3}{2} p[\psi_f + \sqrt{\psi_f^2 + 4(L_d - L_q)^2 I_q^2}] \frac{I_q}{2} \tag{5}$$

In actual control process, it is difficult to calculate the operating point in real time, which is the intersection of two curves. Therefore, we can control voltage U_s, U_{lim} work on as far as possible, and to ensure the current vector tends to weakening control objectives. The obtained MTPA curve, I_{d_min} curve and current limit circle, which compose the working area diagram of weakening control, can be shown in Fig.2. In order to control the stator voltage Us -> $U_{lim,}$ using PI control algorithm to achieve it.

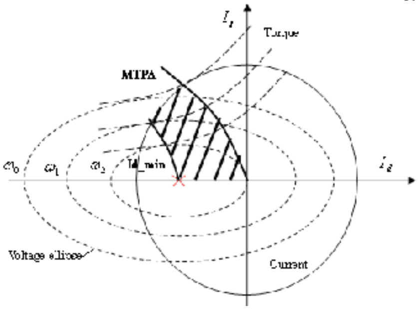


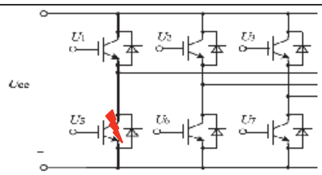
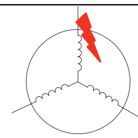
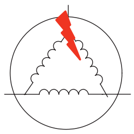
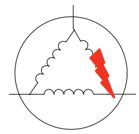
Fig.2. Weakening control work area

3.2. Robust limp-home technology

In combustion vehicle or hybrid EV, if some failure is indicated in motor drive system, either in inverter, or in motor, the whole motor drive system will be switched off, and only use the combustion engine to drive the vehicle. The limp-home strategy of combustion engine is mature enough to make sure the vehicle can run as long distance as possible. But for pure electric vehicle, motor is the single power source, the vehicle can only depend on motor running to leave dangerous area even motor drive system meet big failure suddenly, otherwise the passenger will be stranded in any possible dangerous area, such as high way, hungriness, etc. It will not be accepted by end user.

In order to solve above risk, some robust limp-home technology should be designed for EV motor-driven system. There are several steps to reach this target: 1) analyze the possible failure in EV, especially the motor-driven system. 2) for each failure, the level of Risk level (R), Occurrence (O) and Detection (D) should be identified. 3) based on final score of (R x O x D), some additional concepts should be designed to reduce the risk level, either reduce the occurrence of the failure, or increase the detection possibility. In the automotive industry, the tool of FMEA (Failure Mode Effect Analyze) is used for this purpose.

Table 2. The failure cases of one phase lose

No.	Type	Description	No.	Type	Description
1		One IGBT module damaged.	3		Star connection open
2		Triangular connection open	4		One phase open in triangular connection motor

There are some potential failures in motor drive system: inverter failure (use one phase lose as an example), cooling system failure, DC/DC failure, battery system failure, motor speed overrun, etc. We will analysis these failures one by one. The failure of one phase loses in the inverter or in the motor happens very seldom (Occurrence low), inverter system also can detect this failure (Detection high), but this failure can lead to motor drive system stop running, then the R will be very high (Risk high), some additional limp-home concepts should be designed to decrease the R to a acceptable value, such as make sure motor drive system can still run with limited power/speed even one phase lose happened. Table 2 shows the possible one phase loses in the motor drive system. If the failure of cooling system happened in the motor drive system, as the heat loss of inverter and motor can not be brought out by cooling system, the temperature of the chips will increase very quickly, then the risks of damage the inverter / motor will happen afterwards if without any limp-home strategy implemented (R is high). The occurrence of this failure is normal. When the failure happened, the inverter can detect the failure by motor stator temperature sensor and coolant temperature sensor, so the detection is high. In order to decrease the R, a special power/torque decrease strategy can used to decrease the power/torque of motor drive system based on the detected stator temperature or the coolant temperature. The similar protection approach can be used for battery system failure, e.g. a current/power limitation strategy can be used to protect the battery system when some battery system failure happened. DC/DC is another important component in EV, which converts high voltage DC power to 12 V DC power. This 12 DC power can be used to provide the electric energy for the controllers and some other auxiliaries, such as radio, lamp, etc. The generator that used in conventional vehicle has been removed, but the 12V battery is still used in EV to buffer the energy charging and consumption. That means if DC/DC damaged, 12V battery can still provide the power supply with limited duration. So the R of this failure is middle if the 12V battery is big enough. To void the drive distance is limited by the capacity of the 12 V batteries, there are two possible solutions to prolong the distance: 1) switch off all non-necessary 12 V power consumer automatically or manually by the driver after some lamp indication. 2) design a redundant power supply module only for motor drive system. If DC/DC damaged, this additional power supply module will be turned on immediately to make sure the motor drive system can run as well.

3.3. Torque accuracy

Torque accuracy of the motor drive system will influence on vehicle level drivability, vehicle level energy optimization, response time for suddenly drive torque demand changes, etc. Fig. 3 shows the typical behavior of motor torque accuracy and torque response curve. It is impossible to filter the entire torque ripple, but at least this kind of torque ripple can not lead to drivability problem, so it should be designed and limited to an acceptable range.

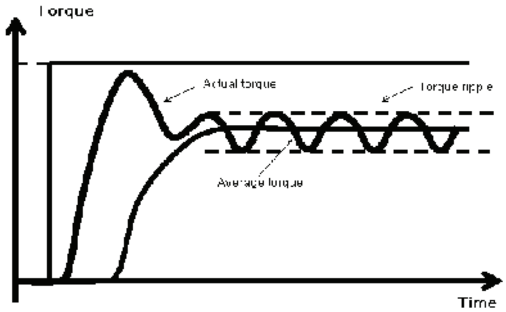


Fig.3. Torque accuracy and response time

In motor drive system, there are many impact parameters on motor control torque accuracy, such as phase current sensor accuracy, rotor temperature estimation accuracy, stator temperature sensor accuracy, position sensor accuracy, IGBT switching strategy, aging, etc. For static parameters, such as position sensor accuracy, calibration optimization job is very important, and try to cover the tolerance of all sensors. But for dynamics parameters, such as aging influence, some additional adaptation algorithm should be designed to learning the aging curve and predicate the possible tolerance.

3.4. Efficiency of motor drive system

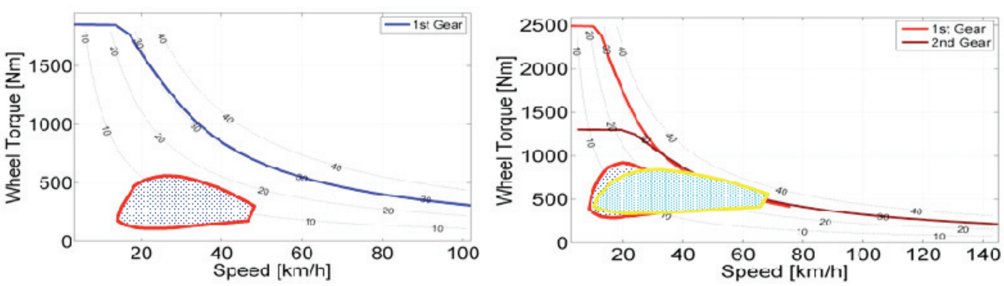


Fig.4. Efficiency area of motor with 1/2 gear

Higher motor drive system efficiency will prolong the EV drive distance, which is currently one of biggest bottle neck of EV usage. There are several approaches to increase motor drive system efficiency: 1) increase inverter switching efficiency by using higher switching frequency and low switching loss IGBT module; 2) use higher efficient motor control algorithm, such as SVPWM (space vector PWM control); 3) special design of motor and set the high efficiency working point close to the real usage points. 4) use 2 gears gearbox to enlarge the motor high efficiency area. Fig. 4 is the comparing of motor high efficiency area between 1 gear and 2 gear. From the figure, we can notice that the high efficiency area of motor has been enlarged more than 50% area with 2 gears.

3.5. Max motor speed limitation

From the simulation result, we can get the draft conclusion: higher motor speed, smaller motor is needed. For example, an EV with one gear gearbox, max vehicle speed normally correspond to max motor speed, then higher max motor speed, a bigger gear ratio can be used with constant max vehicle speed. Bigger gear ratio can decrease the motor torque requirements at low speed, so the space of the motor can be reduced as lower torque requirement. At the same time, the motor torque is some linear relationship with inverter current. Then lower torque requirements will lead to lower inverter current requirements, finally the cost of inverter also can be reduced. But the max motor speed is also limited by the induction voltage of motor winding: higher motor speed will lead to higher winding induction voltage. If this voltage is higher than some threshold, some important power module inside inverter will be damaged, such as IGBT module, etc. So at the motor drive system design stage, the max motor speed should be identified and limited. During real drive, the motor speed can be possible beyond the max speed limit, e.g. EV run in down-hill road. The Risk Level is high as inverter or motor can be damaged at this running conditions. To reduce the Risk Level, some special concepts should be designed: 1) First steps, if the motor speed is still at some allowable range, inverter will try to generate some negative torque to brake the vehicle; 2) Second steps, if the motor speed is near the dangerous range, some mechanical speed limitation should be activated, such as braking system, overrun bypass system, etc.

4. Summary

This paper introduces five key technologies in EV motor drive system design: weakening control, limp-home strategies, torque accuracy, efficiency of motor drive system, and max motor speed limitation, which can be used as a good reference for EV motor drive system design in enterprises and universities.

Acknowledgements

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5. References

[1] Sozer Y, Torrey D. A adaptive flux weakening control of permanent magnet synchronous motors. Industry Applications Conference, Thirty-Third IAS Annual Meeting. 1998, 1:475-482.

[2] Chan C C, Chan K T. An advanced permanent magnetic motor drive system for battery-powered electric vehicles. IEEE Trans.on Vehicular Technology, 1996, 45:180-188.

[3] Vaez Sadegh, Rahman M A. Adaptive loss minimization control of inverter-fed IPM motor drives. IEEE Conference of PESC'97 Record, 1997, 35(5):861-868.